Stress Analysis and Design of the Frame of a Personal Electric Vehicle

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

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(Mr Azman b Zainuddin)

UNIVERSITI TEKNOLOGI PETRONAS
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September 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MUHAMMAD SYAMIL B ZAKARIA

ABSTRACT

Electric vehicles (EVs), as an emerging transportation platform, have been introduced over the past several decades due to various concerns about air pollution and the contribution of emissions to global climate change and due to road congestion. Electric vehicles are the answer and it has evolved to a personal electric vehicle (PEV) which is designed for a single person ride. PEV has a limited range of travel due to limitations of energy from the battery and weight of the vehicle itself that consumes power of the battery. Due to that, chassis of PEV has a potential to help reducing the weight of the vehicle. In this project an analysis on the chassis of sit-on cycle type PEV is made in order to determine the concentration of stress. Therefore, a lighter chassis can be designed without compromise with the necessary strength for convenient riding. The designed chassis is analyzed under working load with various condition of riding including road condition by using a finite element analysis. The reduction of mass from the new design with Aluminum-6061 is 63% without reducing the working load and structural requirement. Aluminum-6061 result with mass reduction on the PEV frame to 2 kg as compared to the Alloy-Steel frame which is 5.5 kg of mass. The reduction of PEV frame is contributed by two major factors which are the material of the frame and the geometry of the frame.

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CHAPTER 1

INTRODUCTION

In this chapter, basically it contains general information about electric vehicle and chassis of vehicle. Besides, it also includes problem statement that relates with the project. The chapter describes the objectives, scope of study and significance of this project.

1.1 BACKGROUND STUDY

Electric vehicles (EVs)

The first electric vehicles of the 1830s used non-rechargeable batteries. Half a century was to elapse before batteries had developed sufficiently to be used in commercial electric vehicles. By the end of the 19th century, with mass production of rechargeable batteries, electric vehicles became fairly widely used. Various types of electric-drive and other clean-fuel vehicles continue to be an interest as a means to control motor vehicle pollution and to control petroleum use in many countries. Since travel behavior is difficult to change, many analysts believe that modifying vehicle technology is the best solution to reduce the environmental impacts of continued increases in vehicle miles traveled (VMT) in areas where automobile use is dominant. Personal electric vehicle (PEV) emerged as a new category of transportation device in the late 1990s. PEV is defined as a vehicle that accommodates a single person over 1-10km distance which uses electricity as energy source [1]. PEV has three main categories which are stand-on scooter, sit-on cycle and mobility scooter as shown in Figure 1.

Generally considered to be a vehicle, sometimes as a motor vehicle or a class of hybrid vehicle, motorized bicycles are usually powered by electric motors or small internal combustion engines. Some can be propelled by the motor alone if the rider chooses not to pedal; while in others the motor will only run if the rider pedals. Some early motorized bicycles were powered by internal combustion engines whereas some utilized electric motors. With lighter batteries and better storage density, the electric motor has recently seen an increase in popularity.

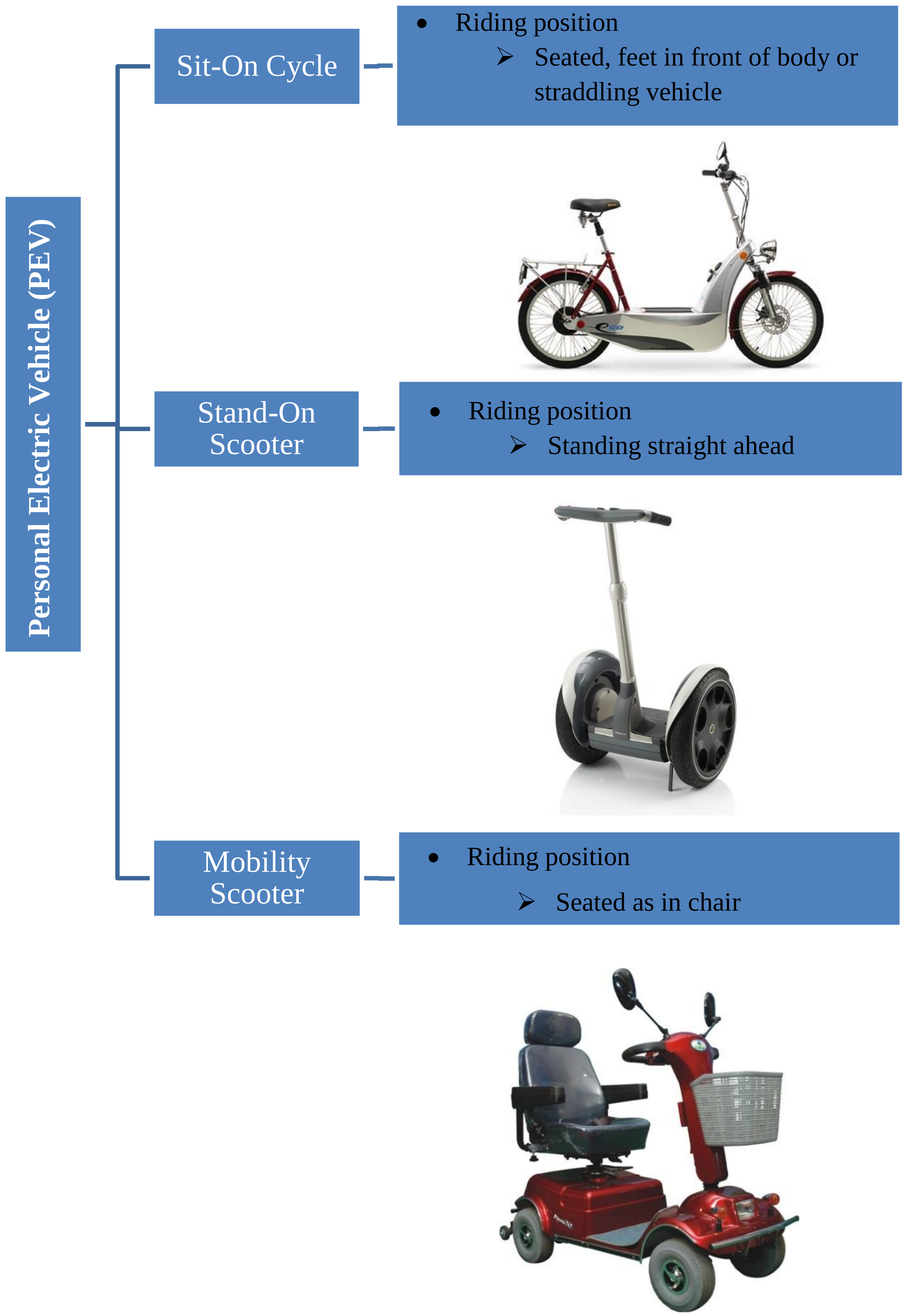

Figure 1: Three categories of personal electric vehicles [1]

Chassis

In ancient years of vehicle design and manufacture, the chassis was the frame above which the body was mounted, and below which the axles were mounted by means of their springs, together with any associated steering and braking systems. In order to achieve similar orders of stiffness in bending and in torsion, a load carrying body could be made lighter and more compact than an unstressed body mounted on a chassis frame. Chassis is the back bone of a vehicle and it will withstand the entire load applied on the vehicle including the passenger and load caused during braking and acceleration. The chassis is the framework to which the various parts of the automobile are mounted. The chassis must be strong enough to bear the weight of the vehicle, yet somewhat flexible in order to sustain the shocks and tension caused by turning and road conditions. Attached to the chassis are the wheels and steering assembly, the suspension, the brakes, and the body.[2]

1.2 PROBLEM STATEMENT

Transportation accounts for two-thirds of our oil demand, and this sector is 97 percent reliant on oil. Electric vehicles (EVs), as an emerging transportation platform, have been introduced over the past several decades due to various concerns about air pollution and the contribution of emissions to global climate change. EVs can be part of an effective mix of strategies to dramatically cut our global warming pollution and oil usage in the transportation sector, including higher fuel efficiency, biofuels, and smart growth. But ultimately, eliminating carbon emissions and oil usage means switching to cleaner fuels, such as electricity and biofuels. Because it will take time for new technologies like plug-ins to replace the more than 200 million conventional gasoline vehicles on the road today, we need to start working on commercializing such technologies right away.

As a solution people come out with an idea to build a transport that is zero in emission and no fuel required. Electric vehicles are the answer and it has evolved to a PEV which is designed for a single person ride. Unfortunately personal electric vehicle PEV is not commercially used due to some constraints on the vehicle itself. First reason is because the price is quite expensive. For a brand new Segway scooter users can expect to pay in the range of $5,350 to over $6,900. Besides, there are a quite number of companies that build this type of vehicle such as Honda, Toyota and Segway. Consequently, this new technology contributes to a high demand in price for the design and secret technology behind this vehicle. In one side, the introduction of the personal PEV has solved a major problem on the air pollution and emissions, but on the other side, PEV itself has some limitations to be commercialized on the market. The reasons are, to build a PEV is very costly due to material used and design especially on the vehicle power source, transmission and chassis. The technical bottleneck that is faced by all PEV is the development of low-cost, light-weight, high-capacity batteries with durable and reliable operation to enable longer drive range.

In this project the author wants to focus more on to have a light-weight PEV. This project is specifically to build a low-weight of a sit-on cycle type frame. Currently, sit-on cycle PEV is about 50kg in mass. Thus, by introducing a low-weight of a PEV, it will consume less power to drive it moving. With the same amount of power and with two different weight of PEV, exactly the low weight will require less power to move and the excess power can be save by reducing the size of the battery. There are various factors that contribute to the weight of the vehicle which include chassis, transmission, fuel-cell and accessories of the vehicle. In order to have a minimum weight, the chassis must be designed at maximum weight versus strength. As PEV has a low power density, weight is an important parameter in determining the overall performance. By providing good weight distribution it will help minimize the overall weight of the vehicle and therefore enhancing its performance better. Figures 1-1 and 1-2 show the weights of sit-on cycle PEV.

Figure 1-1: Ego Helio Cycle M20; Weight 59 kg - [3] EgoVehicles

Figure 1-2: Yamaha Passol: Weight 45 kg – [4] Yamaha Electric Scooter

1.3 OBJECTIVES AND SCOPE OF STUDY

The main objectives of the project are:

- To design the PEV frame that can lead to the reduction in overall PEV weight and comply with the structural requirement.
- To conduct finite element analysis (FEA) on the existing PEV frame and the proposed design.

Scope of Study

- The frame of PEV will be based on sit-on frame geometry
- This project will produce both 3D model and 2D drawing of existing and proposed design. No prototype will be produced in this project.
- This project will be conducted with analysis of frame using finite element analysis (FEA).

1.4 SIGNIFICANCE OF THE PROJECT

This project is needed to be done because result from the analysis in this project can be used to know the most concentrate load on the frame. Therefore, designer can come out with a design that can eliminate unnecessary part on the frame which will result in reduction of the weight of the frame.

Besides, result from analysis can help future study on the material of the frame which is most suitable and reliable for the personal electric vehicle daily operation. The output of this project would be useful to the designers of PEV in selecting the best frame for the PEV.

CHAPTER 2
LITERATURE REVIEW

In this chapter, it consist a literature review about electric vehicle analysis. The analysis specifically is more on static and dynamic of the vehicle.

In every vehicle, weight contributes to the energy consumption from energy source. For electric vehicle, energy from the battery is also consumed by vehicle weight. A frame should be designed with a minimum weight and at the same time it can sustain the applied load. Since 1900's, the issue of weight versus strength became a big focus. As the technology of electric vehicle evolved, weight is an important factor in designing electric vehicle significantly with the low power density's battery available currently.

2.1 Frame

The raw requirement for a frame is that it makes a light and rigid platform, holding the wheels in the same plane. The potential for frame development is immense – a weight saving in the order of 25% and the ability to make radical changes to the frontal area, the weight distribution and the steering geometry. The main consideration for the frame should be the position of the center of gravity and the approximate length of wheelbase, along with the maximum stiffness/weight and minimum frontal area of the bike.[5]

2.2 Structural Considerations

2.2.1 Fatigue

Failure rarely results from static application of normal operating loads. Rather it is due to either excessive loading or fatigue which ultimately leads to breakage. Fatigue results from continual stress reversal. In practice, the stress levels in a structure will be such that many millions of reversals are required to cause a breakage [6].

2.2.2 Structural Efficiency

If the components of a chassis are designed to be sufficiently rigid, strength will not usually be a problem. Hence a good guide to the efficiency of a structure is its stiffness/weight ratio [6]. Common practice is cost is closely related to weight. There are two basic routes to structural efficiency.

1. Use many small-diameter straight tubes in a triangulated frame
2. Use few large-section tubes and rely on their inherent torsional and bending stiffness

2.2.3 Triangulation

Historically, frames developed as tubed constructions and there are plenty of examples of light, triangulated 'space' frames which provide a direct and strong connection. Triangulation gives an immense increase in stiffness in the plane of the triangle. If more than three components are joined together to form a structure in the shape of square, rectangle or polygon of more sides, it easy to deform this shape into a lozenge, diamond or parallelogram because only the joints have to deflect. It can take up new shape without deforming only any of the struts which make up the structure. The stiffness depends entirely on the joints.[5]

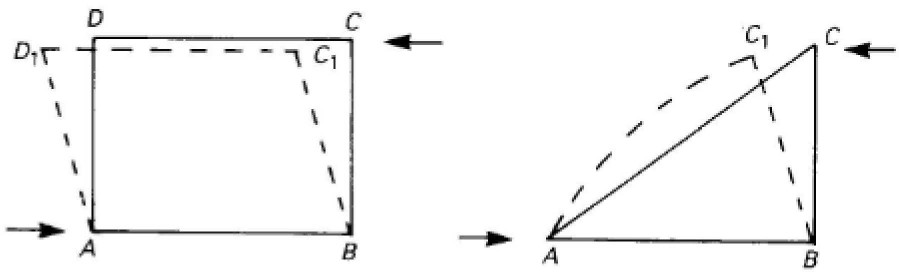

Figure 2-1: Comparison triangles wit four-sided

A triangle makes a much stronger shape than a four-sided figure because to make it deflect at least one side and all the corners have to deform. A four-sided figure can be deflected if only the corners move.

2.3 Frame construction types

Curved tubes

The most widely used kind of frame is made with steel tube that alternate between straight and curved sections welded together.[6]

The basic layout including:

i. Duplex cradle frames wit tubes that start from head- tube area, wrap around the engine, link up the swing arm and lead back to the head-tube.
ii. Frames that can be disassembled, for engine mounting purposes
iii. Open cradle frames, only to one side
iv. Single tube cradle frame which start out from the head-tube and bifurcate around the cylinder or the exhaust tube.

Trellis or lattice-girder

i. Tube may be round or squared, but not bent
ii. Tube are cut and welded together giving rise to lattice structures variously configured in space.
iii. Rigid and lightweight structure
iv. Very delicate to fabricate because of the precision need to create welding and joining between the inclined tubes.

Mixed layouts

i. Casted, box section or extruded sheet or straight or curved tubes are welded together.
ii. Very advanced construction designed and allows the use of materials produced according to the technological process most suited for each particular area.
iii. Thickness of the cast would guarantee adequate stiffness in the structure.

Monocouqe

i. Inspired by automobile frames in which the body has a structural function.
ii. Poor adaptability
iii. Problem for two wheels vehicles is monocouqe frame have a much different form and esthetic appeal than production bike

2.4 Wrought Magnesium in Bicycles frame

The basic properties of magnesium alloys suggest that they would readily find use in bicycles. Magnesium alloys have low density and a high strength to-weight ratio, are readily extrudable, and some alloys are highly weldable [7]. A lack of information about wrought magnesium alloys, a lack of suppliers to complete the production process, and a lack of information in how to set up a manufacturing plant to process wrought magnesium alloys have contributed to only limited market penetration by magnesium into bicycle applications. Many misconceptions limit the acceptance of welded magnesium alloy tubes as an alternative bicycle frame material. Most bicycle product developers believe that magnesium is not weldable and is very brittle. Other common misconceptions are related to safety, with a belief that contact with oxygen or water will cause explosions. Additionally, many feel that magnesium alloys lack sufficient stiffness to make a bicycle frame. The difference between the modulus of aluminum and magnesium is much less than the difference between steel and aluminum. Once these misconceptions are addressed and the basic principles of design are applied, it is believed that the general need for product improvements will push bicycle manufacturers to more seriously consider wrought magnesium as an attractive alternative to steel, aluminum, and even carbon fiber composites

Magnesium frames may be manufactured by die casting or by welding extruded and welded tubes. The weldability rates of magnesium alloys are generally higher than competing aluminum or titanium alloys, or even alloy steels. In fact, magnesium alloys are readily joined using many popular methods of joining to produce a frame. For this reason, welding is the primary method of joining planned for magnesium at present. The weld efficiency is very high and many of the alloys require no heat treatment. Magnesium may benefit from filler metals that differ from parent metals, yet little information is available and most data suggests use of the same filler as parent metals.

Finally, ride quality is a product of integrating frame design, final weight, and material properties. With the high damping properties and low density of magnesium it can easily beat any of the current metals in ride quality. This damping also offers improved fatigue life.

For specifying material used to build the chassis, it is important to know the characteristic of the material especially in shear, axial and torsion resistance. Different materials offer different values, in which to use beams or tube for constructing the frame. In order to obtain maximum reduction of weight, each force on every element that make up the frame should be calculated accurately to get the structurally optimum solution.

CHAPTER 3

METHODOLOGY

In this chapter it describes the methodology of this project through the specific time range. The methodology shows steps that will be taken during this project and it is based on the Gantt chart below.

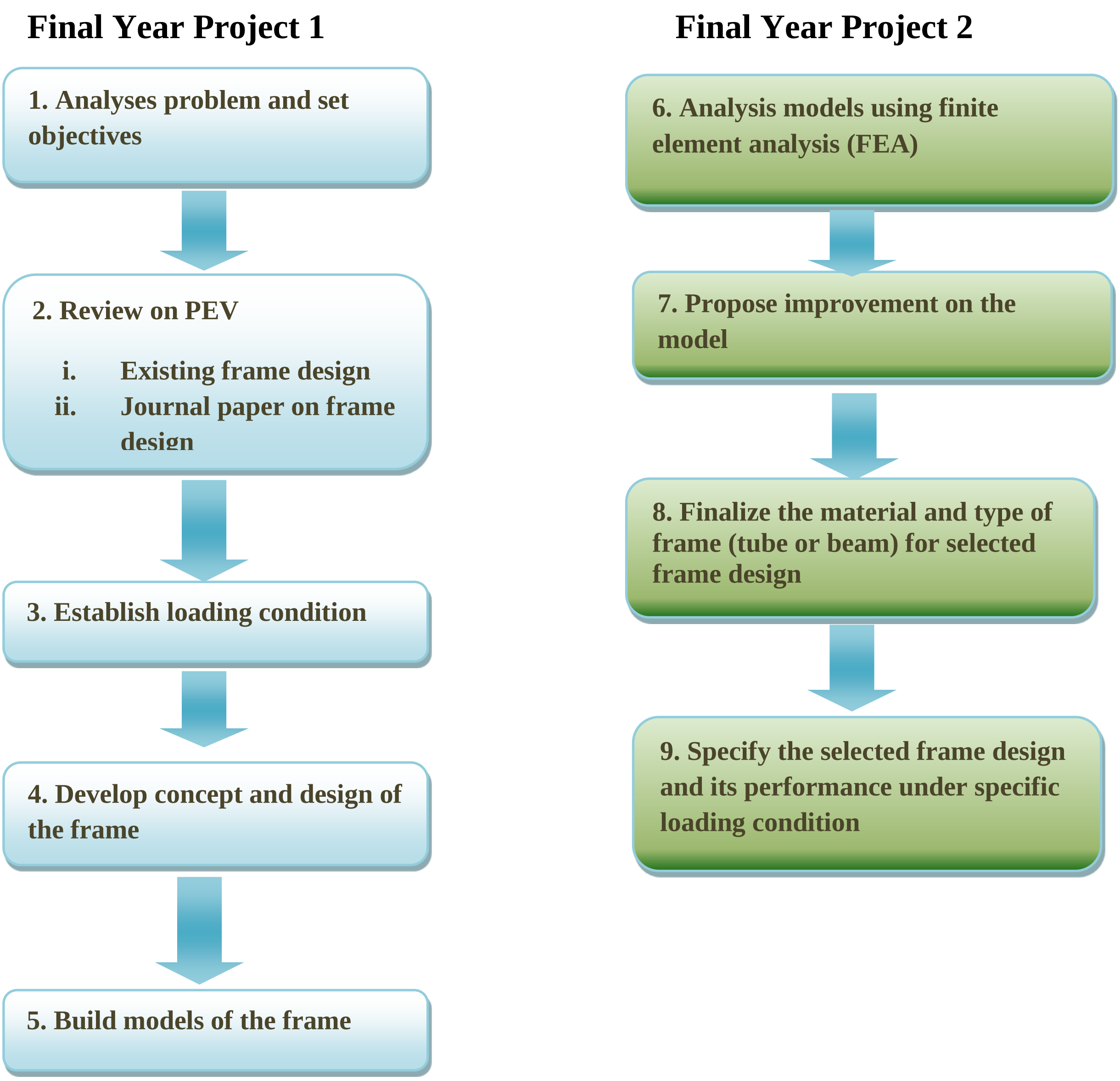

Figure 3-1: Methodology of the project

The project is an analysis base project. Specifically, it is an analysis of ‘Sit-on cycle frame personal electric vehicle (PEV)’. Based on Figure 3-1, first and for most, the project will begin with problem analyses that related to the PEV and the objectives is set based on the problems. With the collective information, the project will proceed with the review of existing frame design of PEV and also journal papers which relate to the frame design. Analysis will cover the sit-on cycle PEV models which are available in current market. Nowadays, there are lots of sit-on cycles PEV available in the market such as eGo 2 Cycle, Yamaha Passol, Lafree-432, and GIANT Lafree which have different characteristics, advantages and disadvantages.

Then, possible load that will act on the frame will be determined based on various parameter of riding condition. It also covers the basic of static and dynamic concept used throughout the analysis of ‘sit-on cycle frame’. The project will continue with development the concept and design of the frame which is suitable for the sit-on cycle PEV. It will include the evaluation on type of frame to be used whether to use tube or beam. After completing concept and design of the frame,a few models of the frame will be built both in sketch and 3D.

FYP 2 will start with the analysis on the built model during FYP 1. The analysis specifically is the finite element analysis (FEA) which is purposely to know the strength and the weakness on the element of the frame. Then, the static and dynamic calculation will be used to propose improvement on the frame to enhance the strength. After completing the calculation, the correlation of the mathematical manner will be fully manipulated in order to obtain optimum design which meets the specific criteria. Then a selected frame design will be specified which this selected design is tested under specific loading condition and successfully achieve the specific requirements.

Lastly, all the studies, discussion and calculation will be finalized based on the selected frame design in the final report. Apart from that, the new design of frame features will be further explain and justifies.

3.1 Research Methodology

Research is a method taken in order to gain information regarding the major scope of the project. The sources of the research cover the handbook of electric vehicle and frame, e-journal, e-thesis and several trusted link.

The steps of research:

1. Gain information of the basic dimension and weight of sit-on cycle PEV from a company – Revolution Manufacturing Sdn. Bhd.

2. Determine behavior of motorcycle and bicycle during traveling.
   a. Static condition
   b. Accelerating
   c. Braking
   d. Climb up the hill
   e. Going down from hill
   f. Travel over a hole and obstacle

3. Identify direction of load act on the motorcycle and bicycle.
   a. Load transfer on the wheel (front and rear) in plane surface
   b. Load transfer during accelerating, braking, climbing and going down from hill.
   c. Location of center of gravity (CG) in different mode of traveling

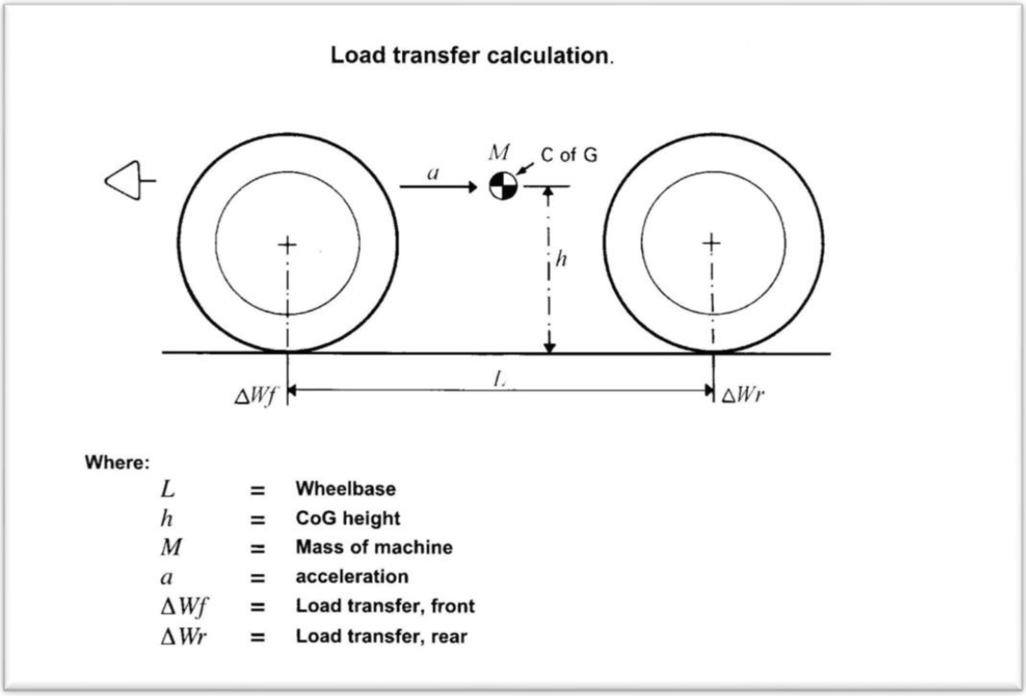

Figure 3-2: Load transfer and center of gravity

4. Identify type of load act on the frame – torsion, axial, tension, compression and etc.
5. Simplify the static and dynamic concept of motorcycle and bicycle to apply on the frame analysis.

3.2 Gantt Chart

Table 2: Gantt chart and Key Milestone

No	Detail/Week	1	2	3	4	5	6	7	Mid-Semester Break	8	9	10	11	12	13	14
	FINAL YEAR PROJECT 1															
1	**Analyses problem and set objectives**															
2	**Review on PEV** **i. Existing frame design** ii. **Journal paper on frame design**															
3	**Establish loading condition**															
4	**Develop concept and design of the frame**															
5	**Build models of the frame**															
	FINAL YEAR PROJECT 2															
6	**Analysis models using finite element analysis (FEA)**															
7	**Propose improvement on the model**															
8	**Finalize the material and type of frame (tube or beam) for selected frame design**															
9	**Specify the selected frame design and its performance under specific loading condition**															

3.3 Software used for the project

Figure 3-3: Software used for 3D modeling and Stress Analysis

Autodesk Inventor 2012 software is used to draw and create 3D model of the designed frame. Besides designing the frame, the software is utilized also to do finite element analysis.

3.4 Dynamic and Static of Motorcycle

In this chapter, briefly it contains the principal of motorcycle behavior travelling in various conditions. It mentions the variety of loads act on the motorcycle which these load affected the motion of the motorcycle. By having the basic of dynamic and static of motorcycle, the frame can be designed at optimum value without ignoring weight and stiffness of the frame.

3.4.1 Basic of motorcycle terminology

For a motorcycle or bicycle there are parameters that should be determined before starting the design process. These parameters are determined based on the application of this two-wheel vehicle.

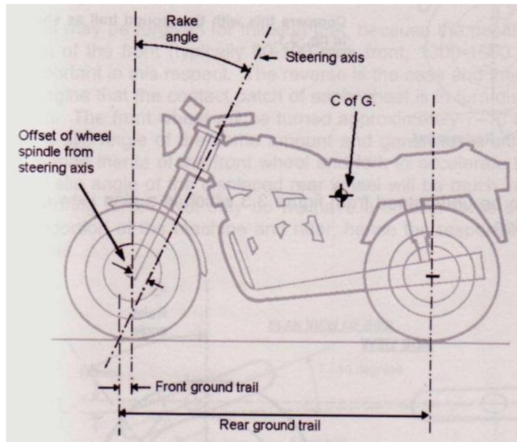

Figure 3-4: Basic parameter of motorcycle

As mention in Figure 4-2, there are a few important parameters for a two-wheel vehicle in order to build the frame. Without knowing these parameters, design and analysis cannot be done on the vehicle.

i. Rake angle

The rake is the angle formed between the neck on the frame of a bike and a vertical line. The bigger the angle, the further out the front wheel will be from the frame.[8]

ii. Trail

Trail is the distance between the point where the tire makes contact with the ground and a vertical line from the center of the front wheel's steering axis to the ground is the bike's trail. In motorcycles it should be always be a positive number -- a negative trail means an unstable ride.[8]

iii. Wheelbase

The horizontal distance between the ground contact points of the front and rear wheels. Wheelbase has a major influence on the longitudinal stability of a bike (along with the height of the center of gravity).[9]

iv. Steering axis

The axis around which the wheel assembly rotates as it turns to the right or left is called the steering axis.[8]

v. Center of gravity

The center of mass of the entire motorcycle, without rider. The exact location of the center of mass is an important quantity in the design motorcycles. [8]

3.5 Governing equation

For a motorcycle or bicycle, there are loads which act on the wheel during stationary and moving. The loads acts on motorcycle are transferred to the frame. To analyze the load there are some equations necessary to calculate the value of load. [6]

3.5.1 Constant motion

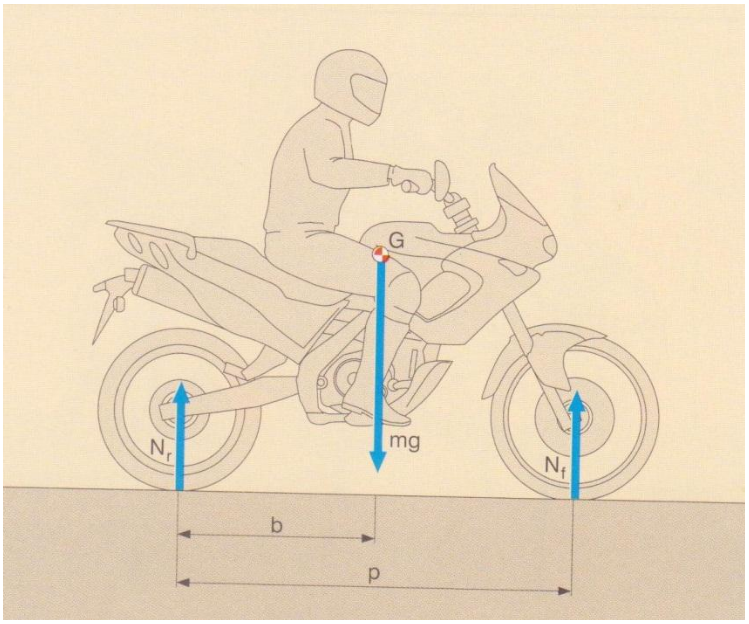

Figure 3-5: Reactions acting on the tires of a bike moving at constant speed

For a constant motion, motorcycle is travelling with no acceleration neither nor deceleration. During constant motion, loads are acted both on the front and rear wheel in positive direction. Another load is the load from weight of rider and motorcycle which act on the negative direction. Motorcycle is assumed as a single rigid body without suspension by using the equation below.

$N_f = mg.\frac{b}{p}$ …………….. (1)

$N_r = mg.\frac{p-b}{p}$ …………… (2)

N_f → load on the front wheel

N_r → load on the rear wheel

b → distance from point of contact of rear wheel to projection of center of gravity

3.5.2 Acceleration

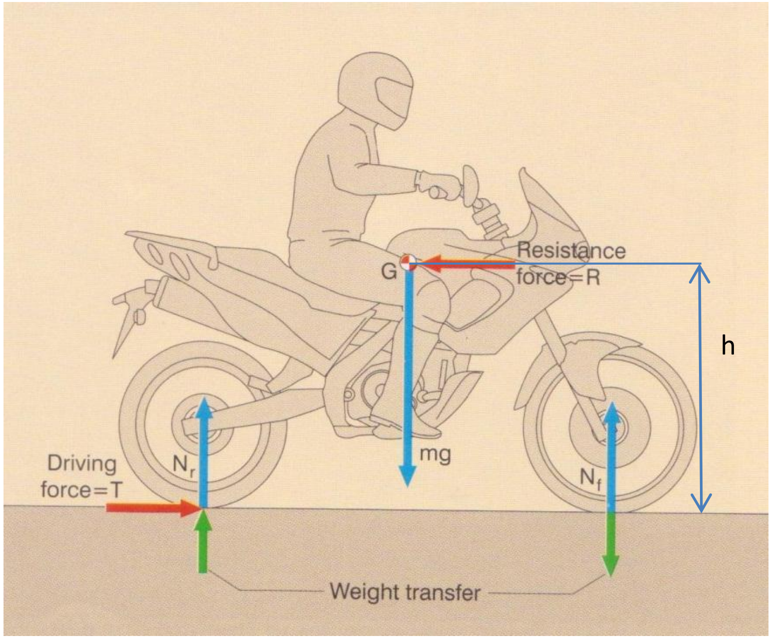

Figure 3-6: Acceleration

In this case, motorcycle is having acceleration. It is different with constant motion as during acceleration there is driving force act on the wheel. This driving force is needed to accelerate the motorcycle. Besides, there is also resistance force which is inertia. Important thing for accelerating is weight transfer. During acceleration, some portion of rider weight is transferred on the rear wheel and result with less weight is transferred on the front wheel. The amount of force transferred is governed by equations below.

$N_f = mg.\frac{b}{p} - T.\frac{h}{p}$ …...………………… (3)

$N_r = mg.\frac{p-b}{p} + T.\frac{h}{p}$ …..……………… (4)

$T = \mu.mg$ ……………………………... (5)

μ → Coefficient of friction

mg → Mass of rider + bike

T → Driving force

3.5.3 Braking

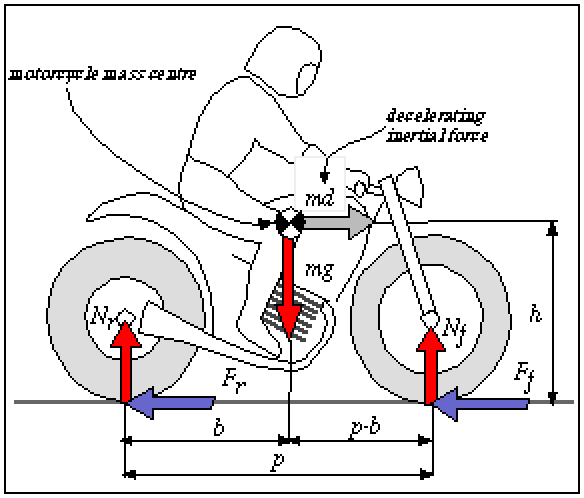

Figure 3-7: Braking

During the deceleration phase, the load on the front wheel increases, while the load on the rear wheel decreases, due to the load transfer. The fundamental equations, applied to the entire vehicle, allow calculating the wheels dynamic load and the transferred load. [10]

i) **Equilibrium of the horizontal forces**

$md = F_f + F_r$ ……………………. (6)

The deceleration inertial force (equal to the product of the mass m with the deceleration d) is equivalent to the sum of the braking forces

ii)**Equilibrium of the vertical forces**

$-mg + N_r + N_f = 0$ ………………. (7)

Weight force mg is equal to the sum of the wheels vertical loads.

iii)**Equilibrium of moments around the mass center**

$-Fh - N_r b + N_f (p-b) = 0$ ………… (8)

F (force of total braking) is indicated the sum of the front braking forces F_f and of the rear braking force *Fr*.

The dynamic load on the front wheel is equal to the sum of the static load and of the load transfer:

N_f = mg. $\frac{b}{p}$ + F. $\frac{h}{p}$ ………………… (9)

While the dynamic load on the rear wheel is equal to the difference between the static load and the load transfer:

N_r = mg. $\frac{p-b}{p}$ + F. $\frac{h}{p}$ ……………… (10)

The load transfer *Fh/p* is proportional to the total braking force, to the height of the center of gravity and inversely proportional to the wheelbase. Assuming the braking force equal to zero, the wheels static vertical loads are found. These are function of the horizontal position of the gravity center.

Static load on the front wheel: N_f = mg. $\frac{b}{p}$ …………….. (11)

Static load on the rear wheel: N_r = mg. $\frac{p-b}{b}$ …………… (12)

In order to avoid tire skidding during the braking phase, the braking force must not exceed the product of the tire dynamic load and of the relative adherence coefficient. This product is the maximum applicable braking force to the tire in adherence limit condition.

Assuming f_f and f_r, the adherence coefficients respectively of the front wheel and the rear wheel, the total braking force in the adherence limit condition is given by:

F = F_f + F_r = f N_f + f N_r………………… (13)

If in the braking phase adherence limit condition is not reached, the braking force depends only from the coefficients of friction from front and rear wheels.

F = F_f + F_r = μ N_f + μ N_r………………… (14)

3.6 Reference model

Figure 3-8: Electric bicycle – GW15ZD / DAIN - Foldable

For this project, reference model is taken from Revolution Manufacturing product which is Electric bicycle – GW15ZD / DAIN – Foldable. The model will create in 3D and will be compared with the designed frame on certain criteria as stated:

i) Weight
ii) Load distribution
iii) Thickness of tube

There are constraints that are put on the designed frame in order to get the boundary of the design to avoid over design.

i) Safety factor used is 2
ii) Maximum mass of rider is 100 kg

CHAPTER 4

RESULT AND DISCUSSION

This section will be discussed the stress analysis that have been conducted and how the result be interpreted. In order to obtain precise analyses, stress applied is put with possible maximum value which can be occurred during moving on the road. In the first part of this chapter, it will explain how the maximum stresses are applied and the result of stress analysis on the reference model Electric bicycle – GW15ZD / DAIN – Foldable.

4.1 Data Collection

As stated in the methodology above, the reference model is built in 3D to conduct the stress analysis. Therefore, the dimension of the reference model is measured. Besides, all parameters including material of the frame and the weight of the frame are also recorded for further analysis. Tables below showed the parameter of the reference model.

Table 3: Specification of GW15ZD / DAIN - Foldable

Features	Specifications
Model Number	GW15ZD / DAIN - Foldable
Electric Driving System	1:1.5 Power Assisted
Frame Length	320”
Wheel Size	16”
Frame	Alloy
Fork	Steel
Brake	Front – Caliper Brake / Rear – Band Brake
Battery	Li-Ion Battery 24V 10Ah
Maximum Speed	20 kmh
Charging Time	7-8 hrs
Battery Life Span	> 500 cycle times
Motor	24V 180W
Riding Distance Per Full Charge	> 45 km
Maximum Load Capacity	75 kg (for optimum performance)
Climbing Ability	7^{o} - 15^{o}

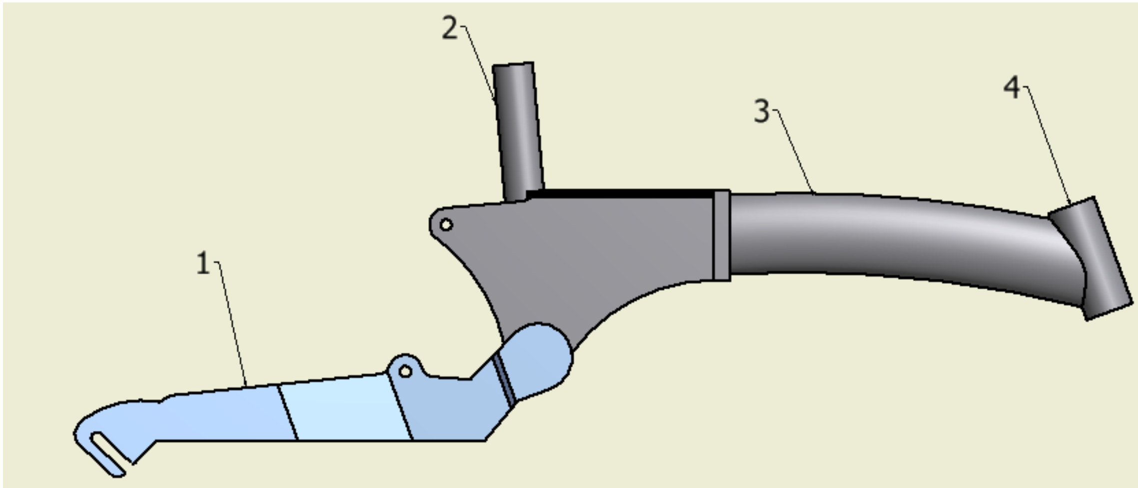

Figure 4-1: Model of reference frame

Table 4: Basic dimension of reference model

Item	**Measured value**
Wheel base	0.96 meter
Rake angle	20^o
Thickness of swing arm (1)	0.005 meter
Thickness of tube (2)Seat tube (3)Top tube (4)Head tube	 0.003 meter 0.003 meter 0.003 meter

4.2 3D Modeling of Reference Frame and Proposed Frame

Based on the dimension measured, a 3D model of reference frame has been built for analysis process. The 3D model is constructed in detail in order to gain precise analysis result, later use to be compared with the designed frame. Figure 4-2 and Figure 4-3 show the drawing of the frame of reference model.

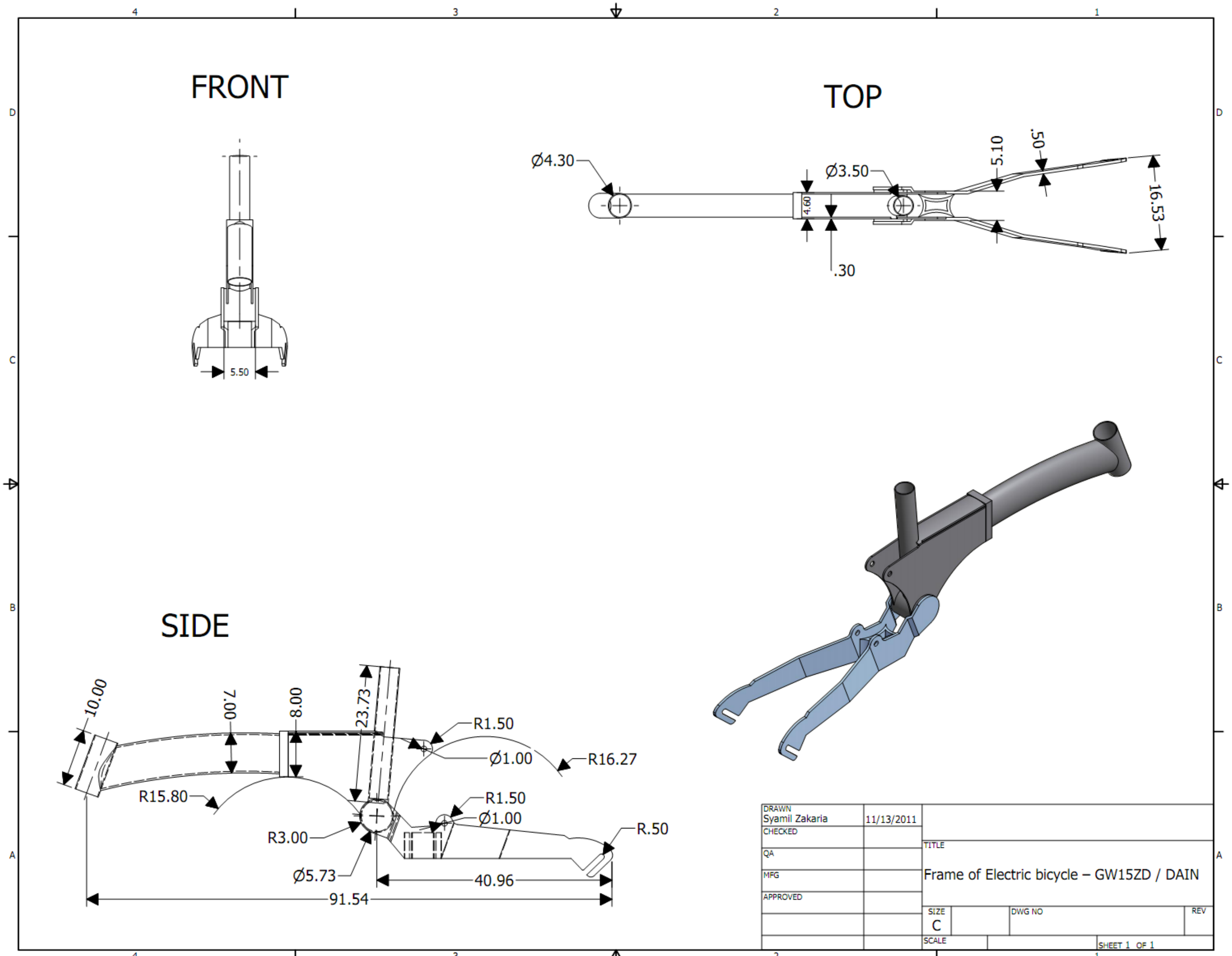

Figure 4-2: Drawing of Electric bicycle frame (Reference model)

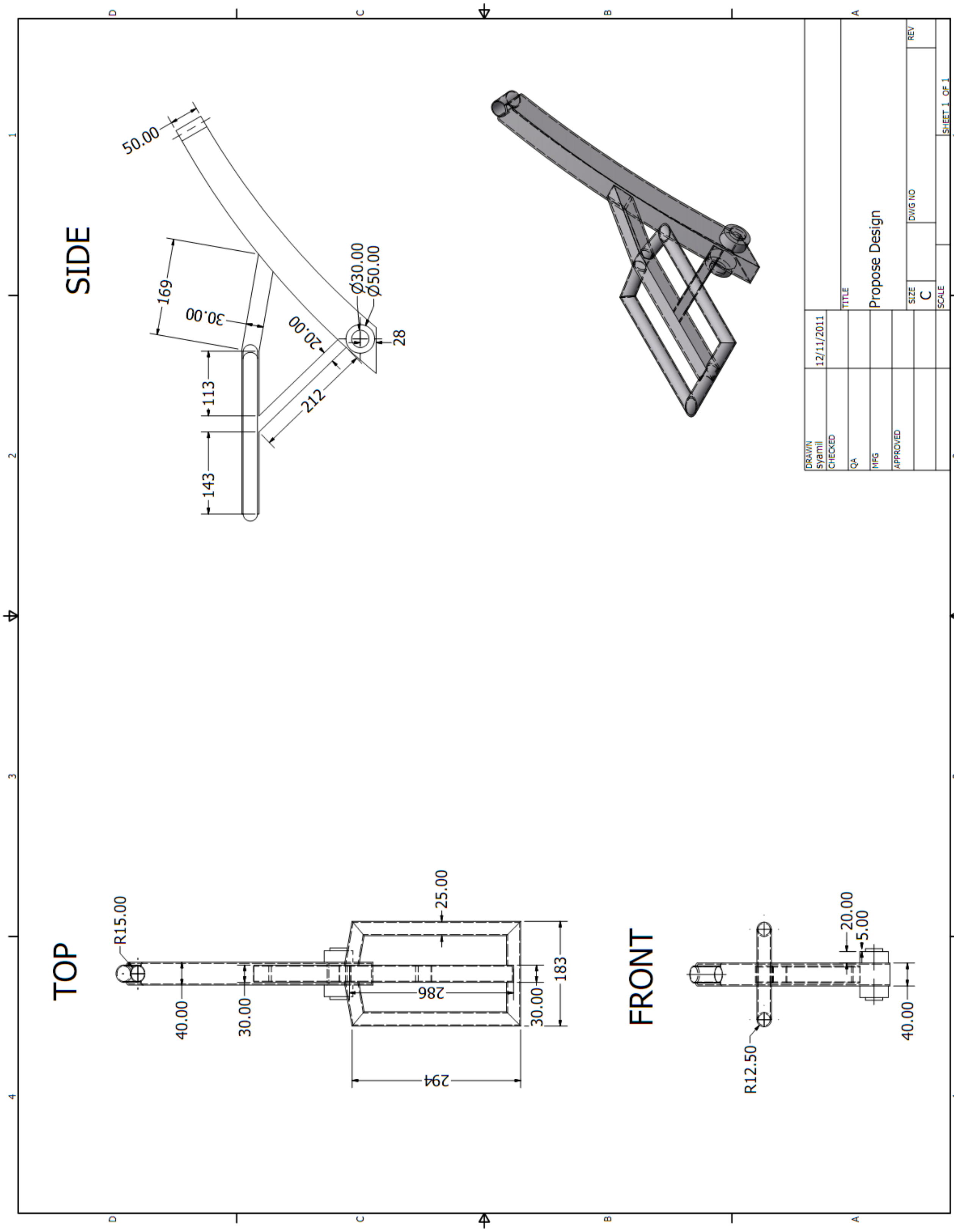

Figure 4-3: Drawing of Electric bicycle frame (Propose model)

4.3 Bump Forces

For the stress analysis, purposely it will result with load concentration throughout the frame. The load introduced to the frame should be the possible maximum load. Therefore in order to obtain maximum load, there is one condition that produces maximum load to the frame. This condition happen when the PEV travel over a specified bump. The largest force on the frame will occur when PEV moves with maximum load at maximum speed over a sharp bump with a height equal to the half of the wheel radius, which is determined by the amount of stopping force (force in negative x direction) caused by the bump.

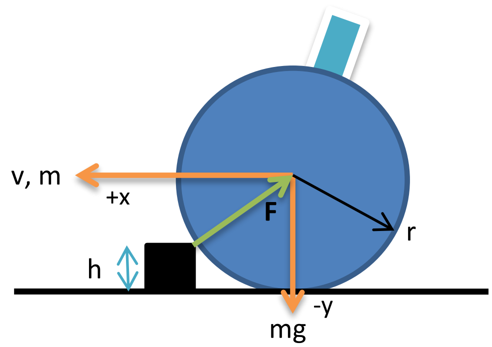

Figure 4-4: Free body diagram of the front wheel of radius r

In Figure 4-4 it shows the front wheel of radius r goes over a bump height h. Notice that the direction of force exerts on the tire causes a reduction in forward velocity as the wheel goes over the bump. As shown in Figure 4-4, a bump exerts both an upward, lifting force and a backward, stopping force on the wheel as it goes over the bump.

In order to determine the force on the wheel, the angle of the force must be known and determined. The angle is determined by this equation:

$$\theta = \frac{\pi}{2} - \sin^{-1}\left(\frac{r-h}{r}\right) \qquad (15)$$

The equation determines the angle between vertical and a line from the impact point with the bump to the center of the wheel, or a line perpendicular to the line tangent to the wheel at the impact point. Using theta and it is clearly that the force moving the wheel over the bump must be greater than downward force (mg).

Thus the upward force acting on the wheel in term of g is:

$$F_y = 1 + r\cos\left(\frac{\pi}{2} - \theta\right)\frac{d\theta}{dt} \quad \text{.................(16)}$$

Since $\frac{d\theta}{dt}$ is equal to $\frac{v_{scooter}}{r}$ when $v_{scooter}$ is held constant, equation 16 becomes:

$$F_y = 1 + v\cos\left(\frac{\pi}{2} - \theta\right) \quad \text{....................(17)}$$

By calculating force in y-direction and the angle of total force on the wheel, the force in x-direction can be calculated geometrically by this equation.

$$F_x = F_y \tan(\theta) \quad \text{............................(18)}$$

4.4 Frame Analysis Based on Bump Forces

For the frame to be introduced with maximum force, PEV is moved with maximum speed and is held constant, thus the both normal forces and bump force are exerted on the front wheel. Based on Table 5, both frame are loaded with maximum load which is 100 kilograms of rider.

Table 5: Driving specification for the frame

Specification	Value
Working load • Rider • PEV – reference model • PEV – propose model	 • 100 kg • 25 kg • 22 kg
Maximum speed	• 20 km/h
Maximum bump size	• 10.16 cm

When PEV moves with constant speed, force exerts on the front and rear wheel are shown below in Figure 4-4.

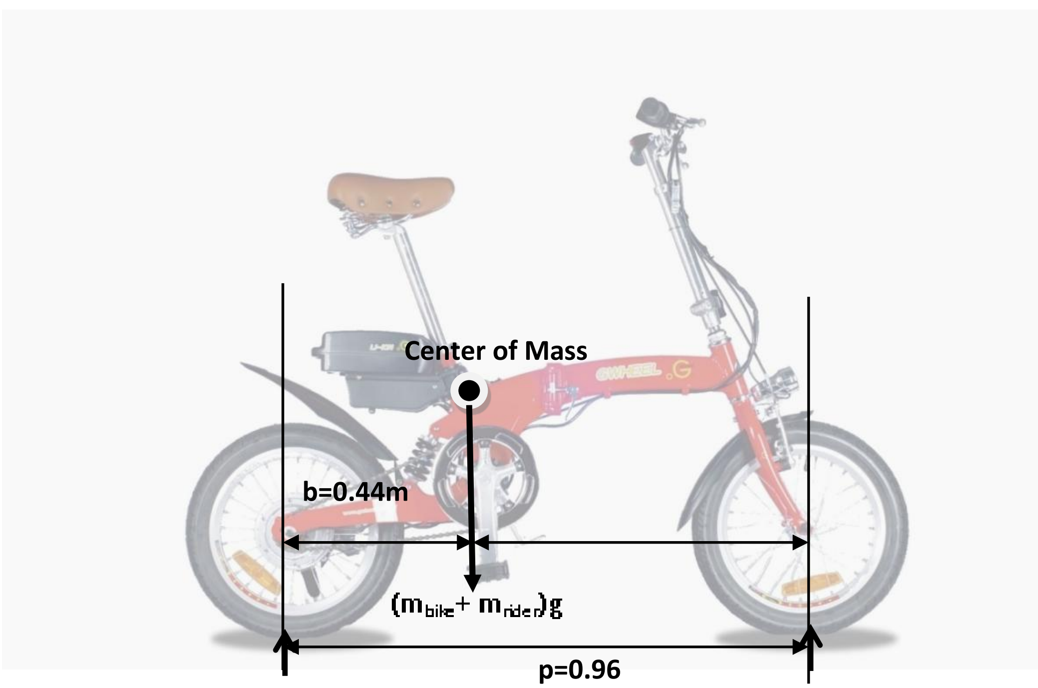

Figure 4-4: Location of center of mass determine the effective masses on both wheels

4.4.1 Calculation for Reference Model

From equation (1), force on the front wheel is:

N_f = mg. $\frac{b}{p}$ …………….. (1)

= $(m_{rider} + m_{pev})$.g.$\frac{b}{p}$

= (100kg + 25kg).9.81 m/s^2 .$\frac{0.44m}{0.96m}$

= 562N

From equation (1), force on the rear wheel is:

N_r = mg. $\frac{\mathrm{p-b}}{\mathrm{p}}$ …………… (2)

= $(m_{rider} + m_{pev})$.g.$\frac{p-b}{p}$

= (100kg + 25kg).9.81 m/s^2 .$\frac{0.96m-0.44m}{0.96m}$

= 664.2N

For forces result from moving over the bump, there are a few parameters that need to be determined. First is the ratio of h/r (bump height/wheel radius) is taken as 0.5. Therefore, as the value of r is known, which is the radius of the wheel, so value of h can be calculated.

h/r = 0.5

h = 0.5 x r

h = 0.5 x 0.2032 m

h = 0.1016 m

As the PEV moves over the bump, there are forces acting in x and y directions need to be determined. For the angle of force it is calculated below:

$$\theta = \frac{\pi}{2} - \sin^{-1}\left(\frac{r-h}{r}\right)$$

$$\theta = \frac{\pi}{2} - \sin^{-1}\left(\frac{0.2032-0.1016}{0.2032}\right)$$

$$\theta = \frac{\pi}{2} - \sin^{-1}(0.5)$$

$$\theta = 60^0$$

For force in y-direction it is determined by equation 17.

$$F_y = 1 + v\cos\left(\frac{\pi}{2} - \theta\right)$$

$$F_y = 1 + 5.555\cos\left(\frac{\pi}{2} - 60\right)$$

$$F_y = 1 + 4.8107$$

$$F_y = 5.8\ N$$

For force in x-direction it is determined by equation 18

$$F_x = F_y\ \tan(\theta)$$

$$F_x = 5.8N\tan 60^o$$

$$F_x = 10.1N$$

As seen in Figure 4-5 below, there are forces in x-direction and y-direction act on the front fork and are transmitted to the frame. In x-direction, force comes from the bump in negative direction while in y-direction forces are from effective masses on the front wheel and force from the bump.

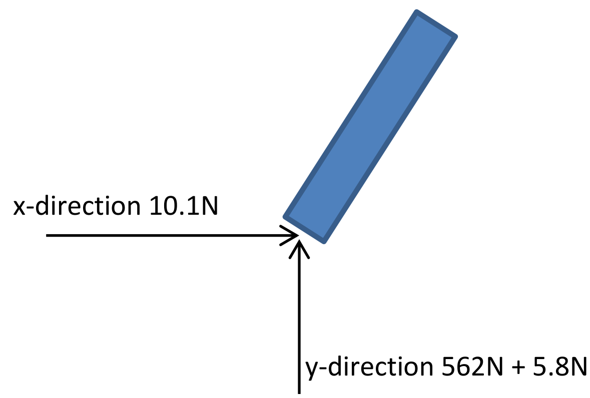

Figure 4-5: Forces act on front fork from the bump

In order to solve the force into normal force and moment on the front fork, force direction is shown in Figure 4-6 below.

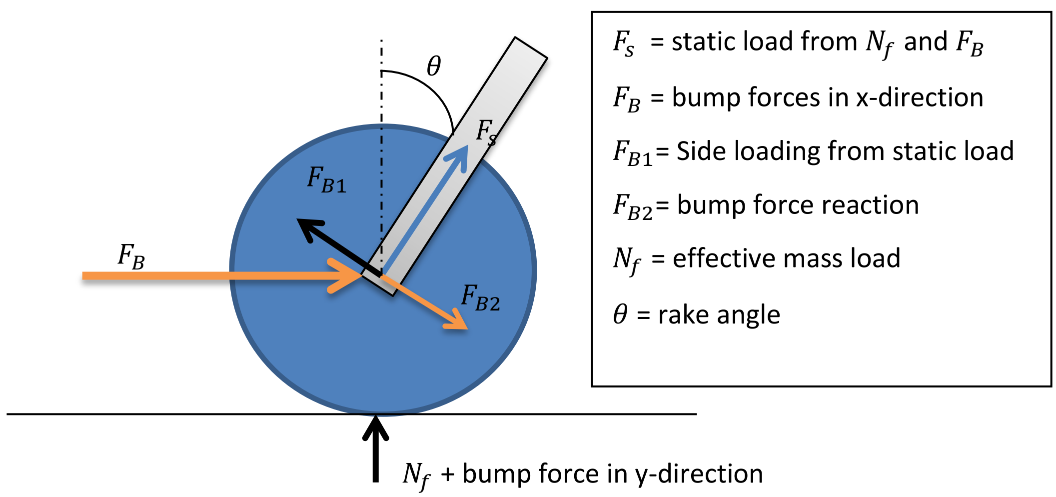

Figure 4-6: Forces component act on front fork

Based on Figure 4-6, normal force is acted in y-axis and moment on the front fork is caused by force in x-axis and consequently the forces are transmitted to the frame. To solve the moment and normal force on the front fork, the following equations are used.

F_{B1}= $N_{f\,+}$ bump force in y-direction. sin θ

= (562 + 5.8)N .sin 20^o

= 194N

F_{B2}=F.cos θ

=10.1N .cos 20^o

=9.5N

Moment=(194-9.5)N x 0.28m

=51.1Nm

For normal force, the following equations are used.

F_s= $N_{f\,+}$ bump force in y-direction. cos θ

= (562 + 5.8)N .cos 20^o

= 533N

F_s = F_B.cos θ

= 10.1N . sin 20^o

= 3.45N

Normal force = 533N + 3.45N

= 536.45N

4.4.2 Calculation for Propose Model

For the propose model, all the parameters for the calculation are shown in the Table 6.

Table 6: Parameters value for propose model

Parameters	Value
p	0.98 m
b	0.34 m
h	0.50 m

From equation (1), force on the front wheel is:

N_f = mg. $\frac{b}{p}$ …………….. (1)

$= (m_{rider} + m_{pev}).g.\frac{b}{p}$

$= (100kg + 22kg).9.81\ m/s^2\ .\frac{0.34m}{0.98m}$

= 415N

From equation (1), force on the rear wheel is:

N_r = mg. $\frac{p-b}{p}$ …………… (2)

$= (m_{rider} + m_{pev}).g.\frac{p-b}{p}$

$= (100kg + 22kg).9.81\ m/s^2\ .\frac{0.98m-0.34m}{0.98m}$

= 782N

Force from Bump

As calculated above, the value for h is 0.5. Therefore this value is inserted in the equation 15 in order to obtain the angle of force acts on the front fork of the frame.

$$\theta = \frac{\pi}{2} - \sin^{-1}\left(\frac{r-h}{r}\right)$$

$$\theta = \frac{\pi}{2} - \sin^{-1}\left(\frac{0.2032 - 0.1016}{0.2032}\right)$$

$$\theta = \frac{\pi}{2} - \sin^{-1}(0.5)$$

$$\theta = 60^0$$

For force in y-direction it is determined by equation 17.

$$F_y = 1 + v\cos\left(\frac{\pi}{2} - \theta\right)$$

$$F_y = 1 + 5.555\cos\left(\frac{\pi}{2} - 60\right)$$

$$F_y = 1 + 4.8107$$

$$F_y = 5.8\ N$$

For force in x-direction it is determined by equation 18

$$F_x = F_y \tan(\theta)$$

$$F_x = 5.8N \tan 60^o$$

$$F_x = 10.1N$$

To solve the moment and normal force on the front fork, the following equations are used.

F_{B1}= $N_{f\,+}$ bump force in y-direction. sin θ

= (415 + 5.8)N .sin 20^o

= 144N

F_{B2}=F.cos θ

=10.1N .cos 20^o

=9.5N

Moment=(144-9.5)N x 0.28m

=37.7Nm

For normal force, the following equations are used.

F_s= $N_{f\,+}$ bump force in y-direction. cos θ

= (415 + 5.8)N .cos 20^o

= 395N

F_s = F_B.cos θ

= 10.1N . sin 20^o

= 3.45N

Normal force = 395N + 3.45N

= 398.5N

4.5 Stress Analysis

The frame is assumed as rigid body constraints since the frame should ideally behave as a rigid body during travel. Before starting the stress analysis, a few constraints are put in the model. As shown in the Figure 4-7 below, constraints are put in 3 positions in order to perform stress analysis cause by bump. These constraints will hold the position of the model in static as the forces are acting on the front.

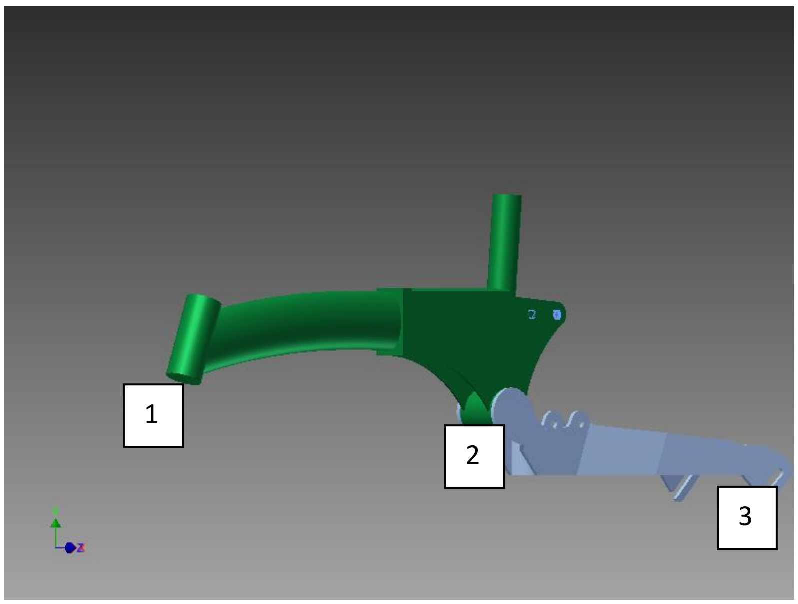

Figure 4-7: Constraint positions on the reference model

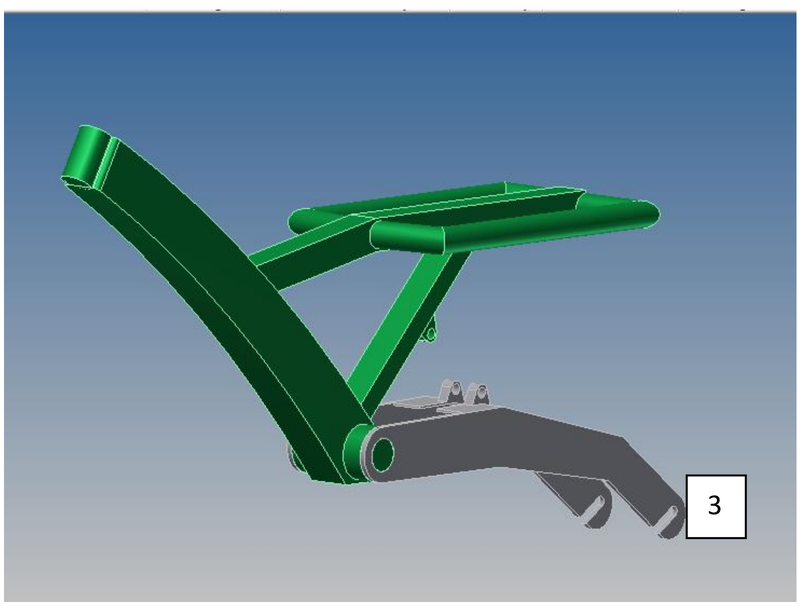

Figure 4-8: Constraint positions on the propose model

By knowing both normal force and moment on the front fork, these loads are applied on the frame in the stress analysis process. Normal force is applied on the head tube as well as the moment creates by the bump forces also exert on the head tube. On the rear, there are effective masses on the rear wheel that are transmitted to the swing arm, while on the seat tube, mass of rider acts in downward direction.

4.5.1 Stress on the Frame

Before starting the stress analysis, the material of the frame needs to be determined to ensure the precision of the stress analysis. Mechanical properties of frame's material are mentioned in Table 7 and Table 8.

Table 7: Mechanical properties of Alloy Steel for reference model

Name	Alloy Steel	
General	Mass Density	7.85 g/cm^3
	Yield Strength	250 MPa
	Ultimate Tensile Strength	758 MPa
Stress	Young's Modulus	205 GPa
	Poisson's Ratio	0.3 ul
	Shear Modulus	78.8462 GPa

[11] Concise Encyclopedia of the Mechanical Properties of Materials

Table 8: Mechanical properties of Aluminum-6061 for proposed model

Name	Aluminum-6061	
General	Mass Density	2.71 g/cm^3
	Yield Strength	275 MPa
	Ultimate Tensile Strength	310 MPa
Stress	Young's Modulus	68.9 GPa
	Poisson's Ratio	0.33 ul
	Shear Modulus	25.9023 GPa

[11] Concise Encyclopedia of the Mechanical Properties of Materials

Forces that have been calculated are applied and simulated in the software as shows in Figure 4-9. For upward direction force, it indicates by point 1, which are normal force on front wheel at head tube and on the rear wheel force on the swing arm. 70% mass of the rider acts through the seat tube while 30% of rider mass acts on the handle bar both on downward direction as indicate by point 2. Besides, a moment from the bump force exert to the head tube at point 3.

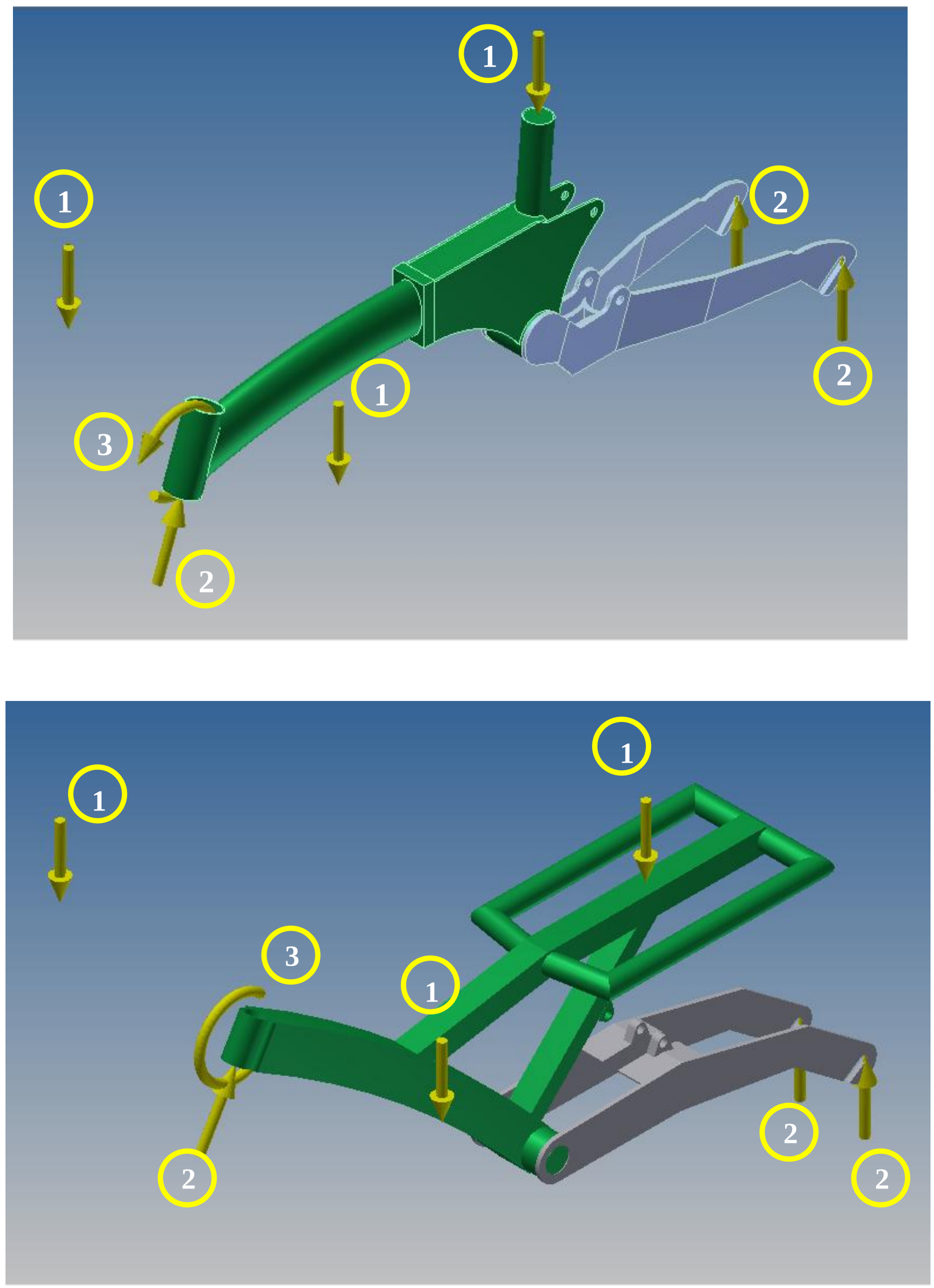

Figure 4-9: Forces applied on the frame

Stress on the reference model

The result of the forces applied is shown in Figure 4-10. From Von Mises Stress, the maximum stress is 140.4MPa which occur between the two swing arms. Average stress occurs on the frame as indicates by the color bar is 100MPa. This stress is still not exceeding the yield strength of the alloy steel. Therefore, the frame can sustain load from the bump force.

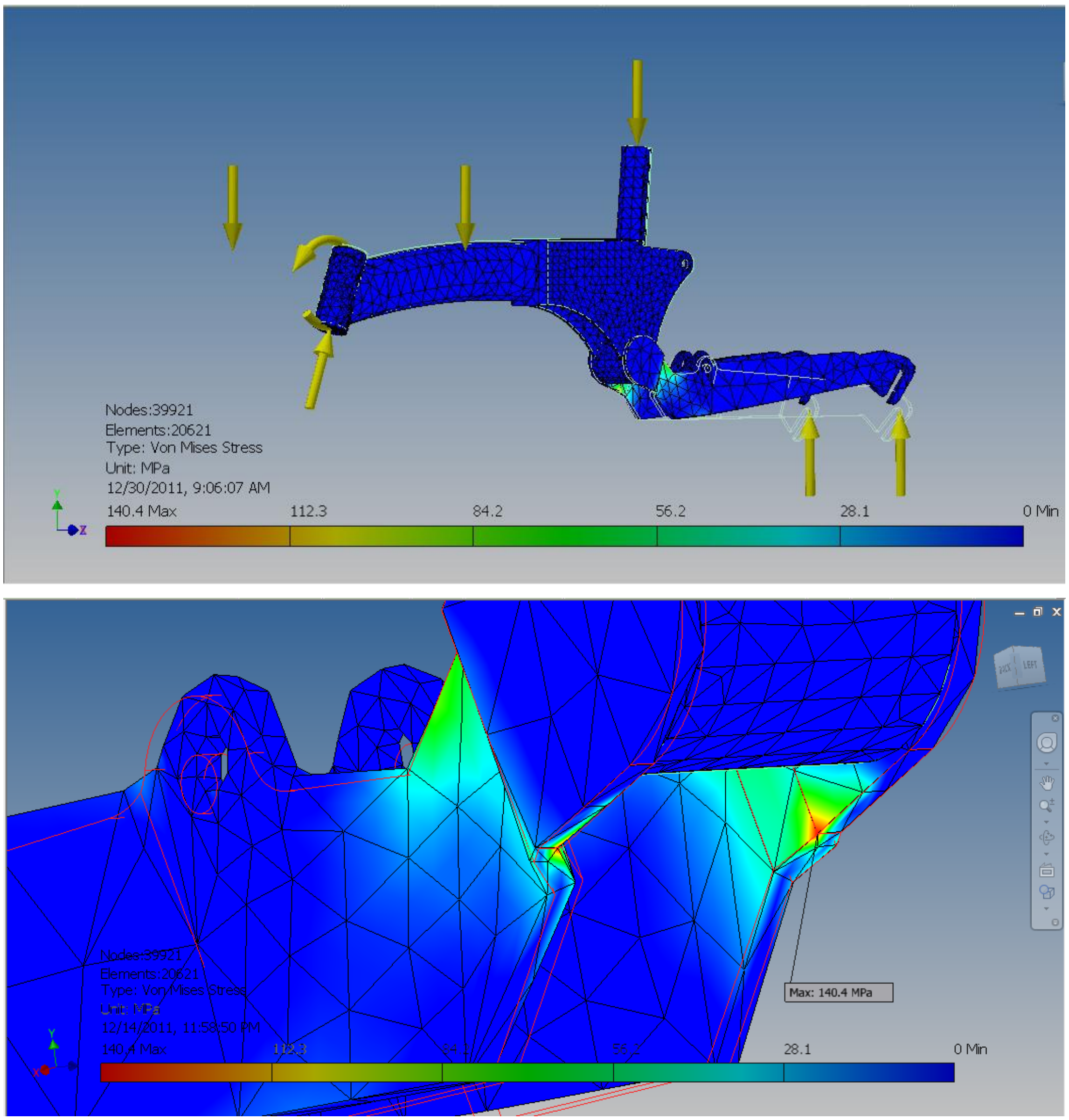

Figure 4-10: Von Mises Stress on the reference frame after exerting with bump force

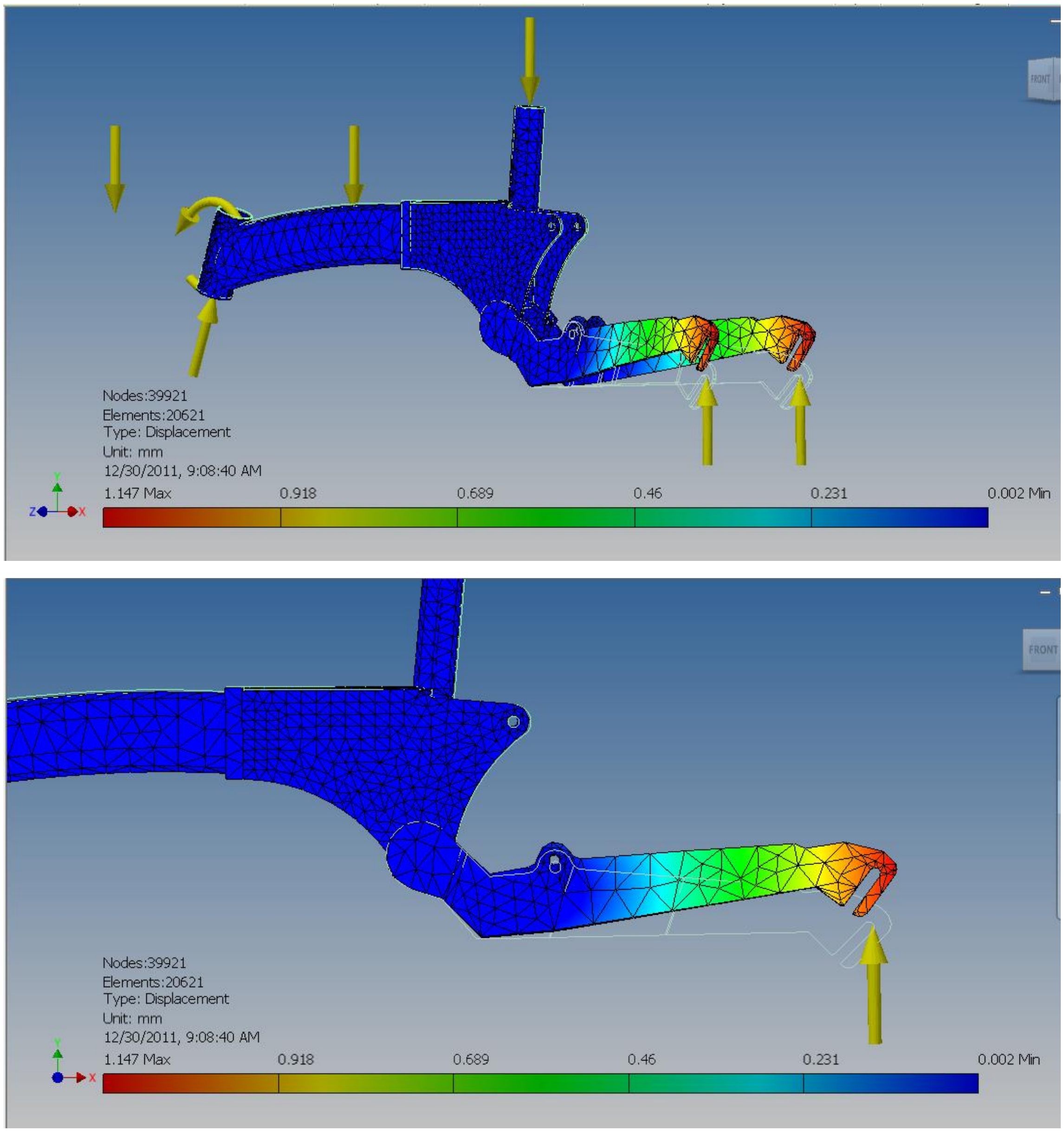

Figure 4-11: Maximum displacement on the reference frame is 1.147mm after exerting with bump force

Stress on the proposed model

The result of the forces applied is shown in Figure 4-12. From Von Mises Stress, the maximum stress is 97.99MPa. Force from the bump is transmitted to the main beam and concentrated between the swing arms as indicate by the shading of color. The maximum stress is still not exceeding the yield strength of the aluminum-6061. Therefore, the frame can withstand load from the bump force.

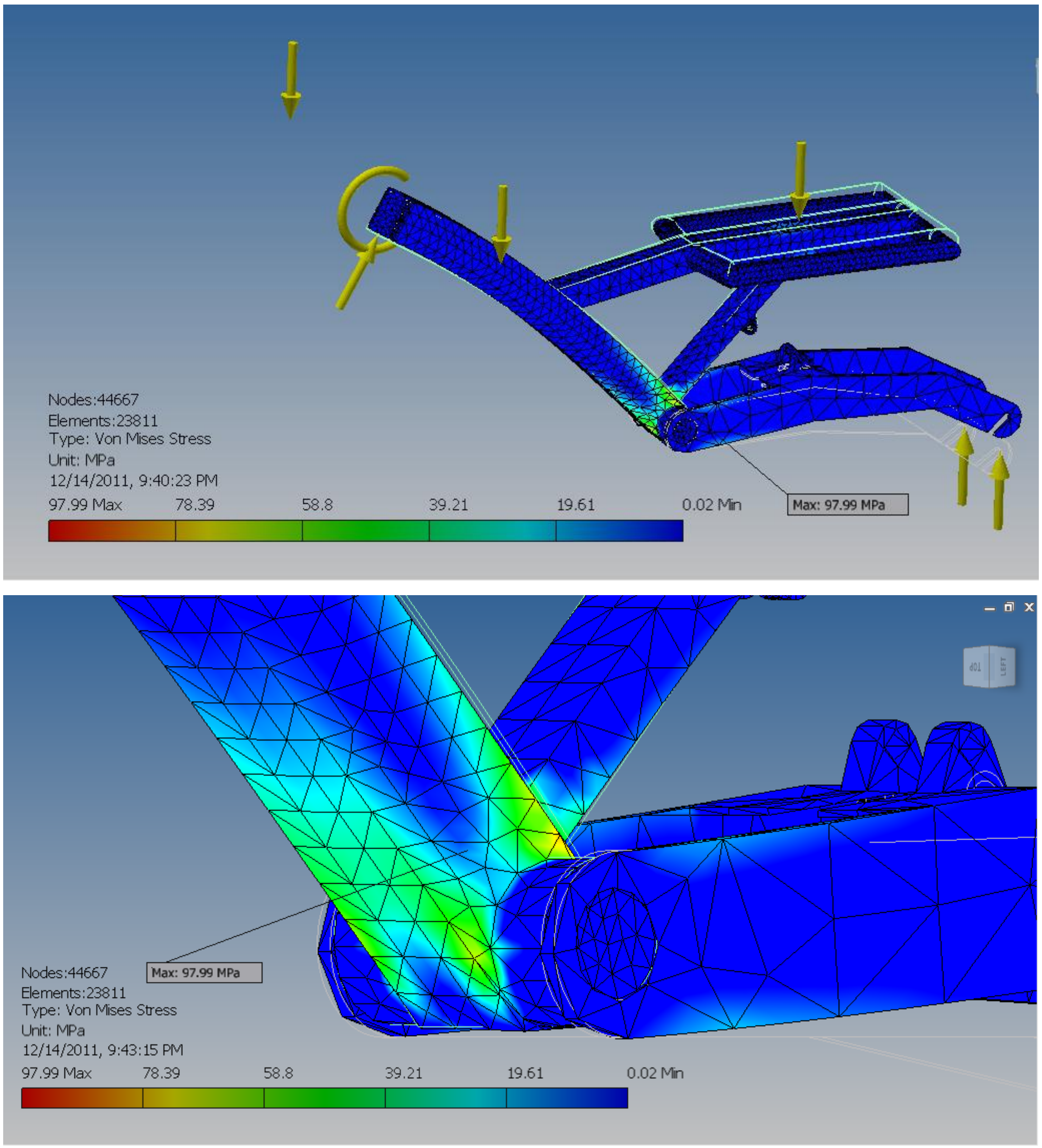

Figure 4-12: Von Mises Stress on the proposed frame after exerting with bump force

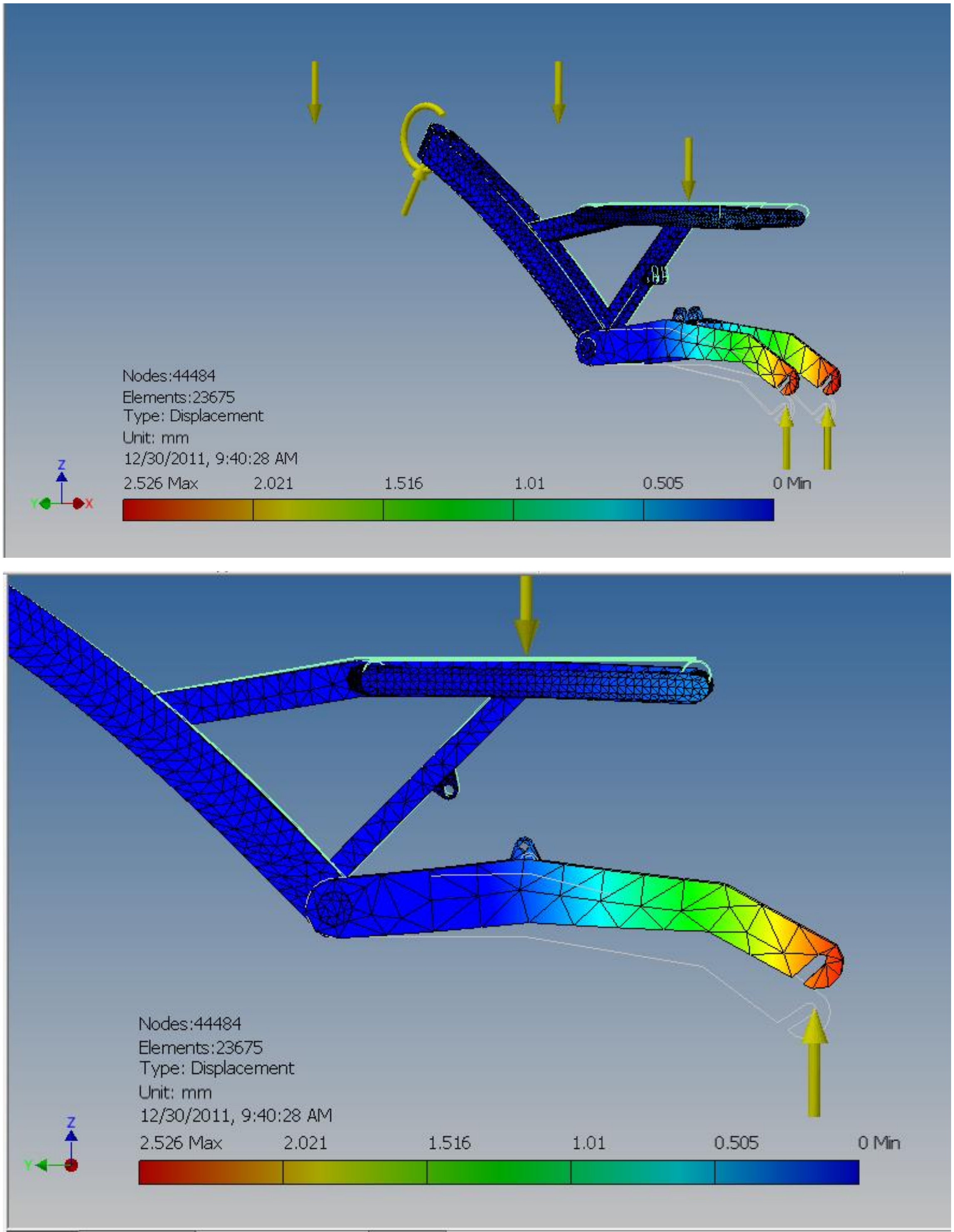

Figure 4-13: Maximum displacement on the proposed model is 2.526mm after exerting with bump force

4.5.2 Proposed frame - Aluminum 6061

After conducting stress analysis on both frame, both frame indicate that the stresses are most concentrated at the center of the frame. Although both reference frame and proposed frame can withstand the impact load cause by the bump, there are very different in mass and geometry.

Figure 4-14: Proposed frame result with 2 kg of mass

By using Aluminum-6061 as the material for design frame, final mass of the frame is 2.04 kg while for existing model the frame mass is 5.5 kg. The reduction of mass from the new design with Aluminum-6061 is 63% without reducing the working load and structural requirement. The choose of aluminum as the material for the proposed frame because aluminum has a low density as well as has high yield strength to ensure the strength of the frame itself. Pure aluminum soft enough to carve but mixed with small amounts of other metal to form alloys, it can provide the strength of steel, with only one-third of the weight. As the objective of the project is to reduce the weight of the frame, therefore aluminum meets the criteria for the frame. Besides, aluminum is also a good metal in corrosion resistance. The metal's natural coating of aluminum oxide provides a highly effective barrier to the ravages of air, temperature, moisture and chemical attack. As a result, the use of aluminum makes the frame to be used in every weather condition without any restriction due to corrosion problem.

The proposed frame is modeled with rectangular tube instead of circular tube. Even though round tubes are superior to square tubes in almost every aspect, but rectangular tube also has its own benefit which it is easy to jig, cope, and weld. Round tubes are generally stiffer per unit weight and have fewer stress concentrations but for PEV frame the forces exert on the frame are not very extreme as compared to the mountain bike or racing bike. Therefore it is sufficient to use rectangular tube for the ease of fabrication process in the future. Frame for the proposed model is designed with constant thickness of tube but different in width and height of the tube.

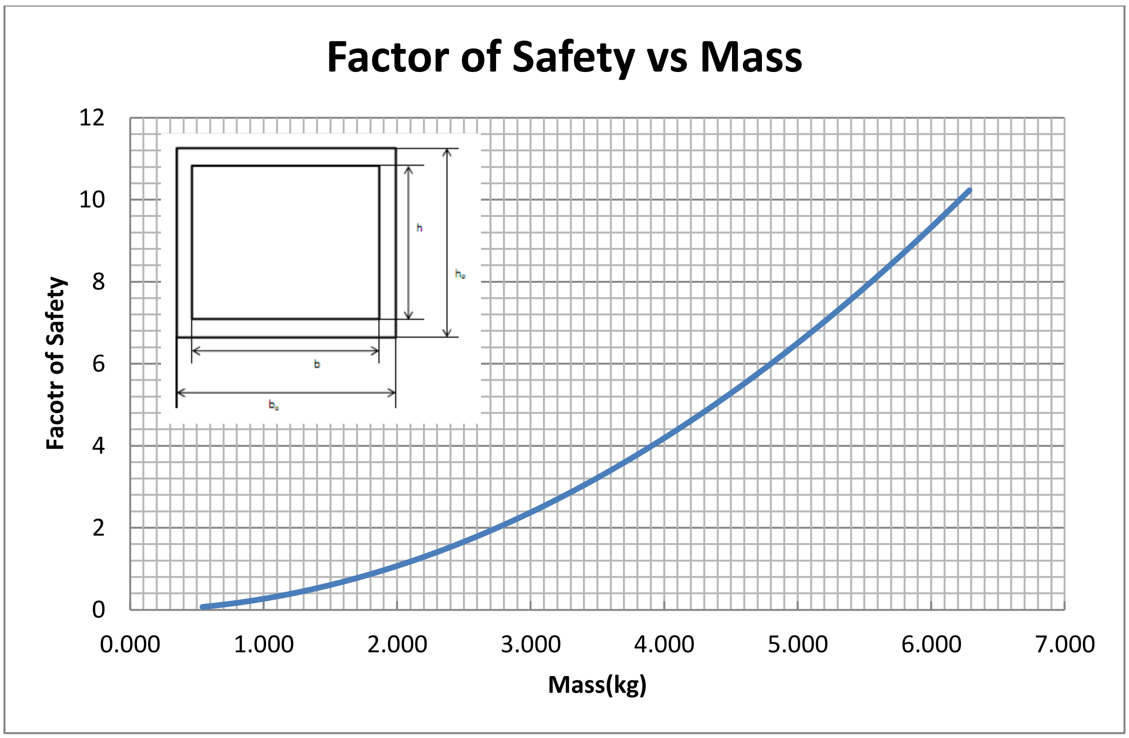

Figure 4-15: Graph of factor of safety versus mass

Figure 4-15 indicates the relation between mass and factor of safety. For this graph, the thickness of the tube is kept constant as 2 mm thickness. As the mass increase, factor of safety also increase. The mass increase with the increasing value of h and b. Therefore, as the value of width, b_o and height, h_o increase then the value of b and h also increase by h_o– 2 and b_o-2.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Aluminum 6061 result with mass reduction on the PEV frame to 2 kg as compared to the Alloy-Steel frame with 5.5 kg of mass. The reduction of PEV frame is contributed by two major factors which are the material of the frame and the geometry of the frame. By choosing the right alloy material it enables good mass reduction without compromising with the stiffness and strength requirement. The result of the stress analysis from the Finite Element Analysis shows the effectiveness of computer aided optimization technique.

Reduction of overall PEV weight will reduce the amount of power need to drive the PEV. Reducing the power needed, drive to the reduction of the battery itself, consequently contribute to the lighter weight of overall PEV. PEV technology is in constant evolution, and the industry is always looking for new designs and new technology. Understanding and mastering the dynamic behavior of a PEV is not an easy task and requires more fundamental and applied research.

5.2 Recommendation

For the future work, this project could be come out with a prototype for the real testing instead of only using the simulation for the stress analysis. A few gauges can be put on the proposed model during the real testing to investigate force introduce to the frame. Then, for future planning, cost analysis can be done in order for the model to be commercialized in the market. The cost analysis includes the material cost, fabricating cost, maintenance cost and etc. Lastly, scope of the project should be expanded to cover not only the frame but also the motor, battery, power train and other accessories. As a result this project can produced an optimum design which all of the major components are specifically design for this type of frame.

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Appendix I: Reference frame - Electric bicycle – GW15ZD / DAIN – Foldable

Appendix II: Support letter from UTP to Revolution Manufacturing

UNIVERSITI
TEKNOLOGI
PETRONAS

9 August 2011

To whom it may concern

Dear Sir/Madam,

<u>REQUEST FOR PRODUCT INFORMATION FOR FINAL YEAR STUDENT'S PROJECT</u>

The bearer of this letter is a student of UniversitiTeknologiPetronas (UTP), Muhammad Syamil b Zakaria, Mechanical Engineering student who is currently doing Final Year Project as required by the university. The Final Year Project is a core course offered to all final-year students of UTP. The duration of this project is 2 semesters which is equivalent to 6 months.

We would be grateful if you could cooperate with us in advance regarding to the acceptance of the student request. Should you require further information, please do not hesitate to contact me at 019-4744841

Your contribution and support toward the success of UTP's program are highly appreciated.

Thank you.

Yours faithfully,

Azman Zainuddin,
Senior Lecturer,
Mechanical Engineering Department,
UniversitiTeknologi PETRONAS
Tel. 05-3687144
Email: azmazai@petronas.com.my

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Corporate Services 605-3688237 Student Support Services 605-3688410 Registrar 605-3688345 Security 605-3688313
Fax: HRM 3656568 Finance 605-3654087 IRC 605-3667672 Student Support Services 605-3667746 Registrar 605-3654082 Website http://www.utp.edu.my

Appendix III: Request letter to Revolution Manufacturing

9 August 2011

Manager,
Revolution Manufacturing Sdn Bhd,

Dear Sir/Madam,

REQUEST CHASSIS INFORMATION OF ELECTRIC BICYCLE (MODEL: MAHSURI)

I am writing to request information of electric bicycle chassis of Mahsuri model from Revolution Manufacturing as my reference for my Final Year Project.

This project briefly is about designing frame for personal electric vehicle (PEV). The designed frame will be analyzed with different load condition using Finite Element Analysis. Together with this letter is detail of information needed from Revolution Manufacturing.

It would be very thankful if you accept this request and hopefully outcome from this project can contribute to the success of Revolution Manufacturing.

Thank you.

Yours faithfully,

Muhammad Syamil b Zakaria
Final Year Student,
Mechanical Engineering Department,
Universiti Teknologi PETRONAS

STRESS ANALYSIS & DESIGN FRAME OF PERSONAL ELECTRIC VEHICLE

Refer to the title of the project; this project objectively is to design a frame for Personal Electric Vehicle. Outcome of this project is a 3D model of the designed frame including the drawing and result of the stress analysis. In order to start this project, it needs a model for reference which the reference model will be taken from Revolution Manufacturing. This reference model will be used to make some optimization on the designed frame through this project.

Table below list the detail information needed.

No	Item description
1	Mass of electric bicycle
2	Mass of frame
3	Frame drawing
4	Frame dimension
5	Frame material
6	Wheel diameter
7	Wheel base